ANYALYSIS OF GPS SATELLITE ALLOCATION FOR THE UNITED STATES

NUCLEAR DETONATION DETECTION SYSTEM (USNDS)

THESIS

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Abstract
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Subject Terms
USNDS, heuristic, GPS, nuclear detonation, knapsack problem

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Abstract

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ANALYSIS OF GPS SATELLITE ALLOCATION FOR THE UNITED STATES NUCLEAR DENTONATION DETECTION SYSTEM (USNDS)

I. Introduction

Background

Despite the end of the Cold War and the existence of both non-proliferation and test ban treaties, nuclear weapons related issues remain at the forefront of national policy. This is due in part to the increased availability of nuclear materials and the irresistible lure of becoming a nuclear superpower [Blocker, 48]. As recently as 28 May 1998, Pakistan announced that it conducted five nuclear tests in the wake of a series of five nuclear test detonations conducted by India in the same month. "Global Engagement: A Vision for the 21st Century Air Force" predicts that there will be a more rapid spread of nuclear weapons and an increases chance of limited attacks on the U.S. homeland resulting from new and unpredictable opponents [USNDS Strategic Plan, 5].

The United States maintains a vigilant role in the continued effort to deter and detect nuclear detonations. In 2001, $36.4 million dollars were allocated to monitoring nuclear explosions [DOE National Security R&D Portfolio, 83]. The mission of the United States Nuclear Detonation Detection System (USNDS) is to "provide worldwide, highly survivable capability to detect, characterize, locate and report nuclear detonations and associated data: in earth's atmosphere and near space, in near real time, and support three national-level missions"[USNDS Strategic Plan, 2].

The three USNDS missions areas and those with primary responsibility for those areas are:

1. Integrated Tactical Warning and Attack Assessment (ITWAA) - United States Space Command (SPACECOM)

2. Nuclear Force Management (NFM) - United States Strategic Command

3. Nuclear Treaty Monitoring (TM) - Air Force Technical Application Center (AFTAC)

Each mission specifies unique event detection requirements with respect to event yield, event altitude, atmospheric environment, and event reporting. SPACECOM has overall management responsibility for the operational NDS to include space and ground segments. NDS ground processing is done at the Mission Control Station (MCS) located at Buckley Air National Guard Base, CO. The Satellite Operations Center (SOC) is operated by the 2^{nd} Satellite Operations Squadron at Schriever AFB, CO. The SOC, with AFTAC support, is responsible for optimizing operations of the space segment [NDS CONOPS, 5].

By the year 2020, the USNDS is to be fully integrated into the US Atomic Energy Detection System (AEDS) which will be a fully integrated portion of an International Atomic Energy Detection System. These systems will be part of the global capability to identify and monitor the growing number of non-proliferation and test ban treaty violators for application of sanctions [USNDS Strategic Plan, 5].

NDS consists of a suite of sensors aboard Global Positioning System (GPS) satellites and the associated ground systems responsible for monitoring the surface of the earth, the atmosphere, and the near space environment for nuclear detonations. AFTAC

uses Global Positioning System Modeling and Simulation (GPS/MS), developed at Sandia National Laboratories, to assess its global coverage with respect to its various mission requirements.

As the prominence of the Global Positioning System's navigation mission continues to grow, so does the number of satellites in orbit. At present, there are 29 operational GPS satellites in orbit, with a new block of satellites (IIF) scheduled for future launch [USNDS Strategic Plan, 5]. Unfortunately, the original NDS ground system design is limited to monitoring 24 satellites at time. Any satellites in excess of the 24 monitored by NDS are designated as spares. While those satellites designated as spares continue to broadcast NDS information, the ground station does not allocate time to receive information from the spares. The constellation of GPS satellites represent 3 block types (II, IIA, IIR) with varying states of health. Although future plans to upgrade the NDS infrastructure exist, at present, AFTAC is principally responsible for nominating which 24 satellites are monitored by NDS from the current constellation. The capability to alter the set of 24 satellites being monitored and those designated as spares is readily available. However, the task associated with choosing 24 of 29 satellites represents over 590,000 unique combinations. The computational effort required to evaluate each combination can be impractical, particularly if a number of changes occur in a year.

Problem Statement

Though informal research has been conducted, AFTAC does not posses a well-defined methodology for selecting which 24 satellites should be monitored by NDS to maximize global coverage. The current method for determining which satellites are

designated spares has been described as "piecemeal" [Holtgrave]. Spares are generally assigned based on the states-of-health of the NDS components on each satellite. The 24 healthiest satellites with respect to NDS are chosen with some consideration given to not allowing too many spares in one orbit plane. The concept of satellite health, however, is very subjective; neither a specific numerical method nor objective means to determine NDS health has been formally established.

Research Objectives

The overall objective of this research effort is to provide AFTAC with a well-defined methodology for selecting which 24 GPS satellites should be monitored by NDS to maximize global coverage of nuclear detonations. The methodology is robust in design to account for the anticipated future changes in the constellation, allowing it to be a useful tool well into the future. The research also includes an investigation into which parameters have the most significant contribution to a satellite's contribution to coverage. The results from the methodology are aimed to meet or exceed the current state of coverage.

Methodology

The first step taken in attempting to maximize satellite coverage was determining which parameters influenced a satellite's ability to detect and report nuclear detonations. When possible, the critical parameters were quantified and combined to produce an estimate of each satellite's value with respect to coverage. Because the satellites are constantly in motion and each satellite's position with respect to the other satellites continuously changing in three-dimensional space, satellite interaction is not readily

numerically quantifiable in a tractable fashion. However, these interactions are an important part of coverage.

The nature of the problem appeared to fit the structure of a knapsack linear program. However, because of the difficulty involved in accurately representing satellite worth, a strictly deterministic approach was ruled out. A heuristic approach was constructed that builds on insight gleaned from previous research to generate a set of likely good solutions. The heuristic was evaluated based upon robustness and solution quality. Robustness was determined by the ability of the heuristic to consistently produce solutions yielding high coverage for a variety of inputs. Solution quality was evaluated based on proximity to the upper bound.

The remaining chapters will elaborate the background information, methodology, data analysis, conclusions, and recommendations for future research. Chapter 2 is dedicated to providing historical perspective and pertinent background research specific to the problem. This research constitutes the basis for the methodology presented to solve the problem in Chapter 3. A detailed analysis of the results is found in Chapter 4, and Chapter 5 summarizes the significant conclusions and provides suggestions for future research.

II. Background

Overview

Beginning with the endorsement of the Limited Test Ban Treaty in 1963, the United States (U.S.) has recognized the advantage of using space-based resources to monitor nuclear detonations. The U.S. has a clear interest in monitoring international nuclear activity. There is a long history of international diplomacy regarding nuclear arms development and proliferation. Due to the unique characteristics governing nuclear phenomenon, space based detection devices have proven to be an invaluable asset to monitor nuclear activity. Utilization of a constellation of satellites provides an efficient means to monitor the entire surface of the earth simultaneously [USNDS CONOPS].

The development of the NAVSTAR GPS satellite program in the 1980's provided an ideal global coverage platform from which NDS could piggy-back. The original GPS constellation was designed to include 24 satellites (21 active, 3 spares). Correspondingly, the NDS ground system was designed to monitor NDS data from 24 satellites. Currently, there are 29 operational GPS satellites in orbit capable of providing NDS data with more satellites scheduled for launch in the near future. The active constellation includes satellites from three distinct block types with individual varied component states of health. In order to maintain the best global coverage possible, efficient techniques must be developed to get the most out of the available resources [Parkinson, 10].

A large amount of research has been devoted to designing satellite constellations for continuous whole earth coverage; however, there is limited research on managing existing constellations and their failure modes. From an operations research perspective,

the issue of selecting satellites to maximize coverage represents a combinatorial optimization problem. Both deterministic and heuristic techniques have been used to solve this class of problems.

History

When President Kennedy and Chairman Khrushchev signed the Limited Test Ban Treaty (LTBT) on August 5, 1963, one of the conditions was that each party to the treaty could use its own technical means to monitor the ban on nuclear testing in the atmosphere or in space. The relationship between the United States and the members of the former Soviet Union has greatly improved since the early steps taken by Kennedy and Khrushchev. However, now nuclear technology has widely diffused throughout the world [USNDS Roadmap].

The second significant international nuclear arms management agreement was the Non-Proliferation Treaty (NPT), originally signed by the U.K., U.S., and Soviet governments on 1 July 1968. This treaty bans nuclear weapons development by its signatures, which currently includes over 140 countries. Notable non-signatures include India, Pakistan, Argentina, Brazil, and Israel [Higbie, 48]. The signing of the Comprehensive Nuclear Test Ban Treaty (CTBT) in September 1996 was a turning point in history, creating for the first time an international norm against all nuclear testing [DOE National Security R&D Portfolio, 80]. Should either of these treaties fail, the United States must still posses the capability to detect clandestine nuclear tests conducted anywhere in the world [DOE National Security R&D Portfolio, 81].

The Vela satellites were developed as the first space based observation devices in a joint effort by the U.S. Air Force (USAF) and the Atomic Energy Commission. The USAF launched the first Vela satellite almost 40 years ago on 17 October 1963. Vela was based on the experience obtained from developing the measurement instruments for the rockets flown during the Dominic series of atmospheric nuclear tests conducted in1962. Vela represented a quick response to the LTBT [USNDS Strategic Plan, 9].

Originally, ten Vela satellites were to be built. However, the first six satellites were so successful, reliable, and long-lived that the last four were never launched. The Vela satellites monitored compliance with the NTBT and provided scientific data on natural sources of space radiation for many years. The least successful of the original Vela satellites operated for ten times its design lifetime of six months. The last of the advanced Vela satellites was deliberately turned off on Sept. 27, 1984, over 15 years after it had been launched. From initial deployment to program termination, Vela was one of the Air Force space program's greatest success stories [www.fas.org].

NAVSTAR GPS is a space-based radio-positioning system consisting of a constellation of 24 orbiting satellites which provide navigation and timing information to military and civilian users worldwide. The constellation provided global coverage and thus an excellent platform to deploy future generations of space based nuclear detection sensors [Parkinson, 36].

Nuclear Phenomenology

Space based sensors provide an unparalleled field of view for optical sensors and a platform to monitor the effects of an atmospheric nuclear blast. The physical output

(light, gamma rays, X-rays, and neutrons) from a nuclear explosion, as well as secondary effects due to the interactions with the atmosphere of these primary forms of energy output is well known. A standard reference for a detailed discussion of these phenomena is Samuel Glasstone's book *The Effects of Nuclear Weapons*, first published in 1950. Measuring the outputs of an event using instruments sensitive to different phenomena helps prevent incorrectly identifying an event due to some natural occurrences (for example, a lightning flash) as a nuclear detonation. The sensors onboard GPS satellites have been designed to measure the outputs due to the various phenomena. In particular, visible light, radio waves, and X-rays are measured. In addition, background measurements of the radiation environment are performed by instruments on some of the GPS satellites [Parkinson, 36].

An exoatmospheric nuclear detonation will release enough elementary particles and photons that can travel huge distances through the void of outer space and be detected by instruments on a spacecraft. Similarly, a nuclear detonation within the atmosphere, endoatmospheric, also generates uniquely characteristic phenomena and signals that support detection by space-based instruments. Figure 1, taken from the USNDS Project Officer Workbook, illustrates the detectable physical phenomenon for nuclear detonations at different levels in the atmosphere [USNDS Project Officer Workbook].

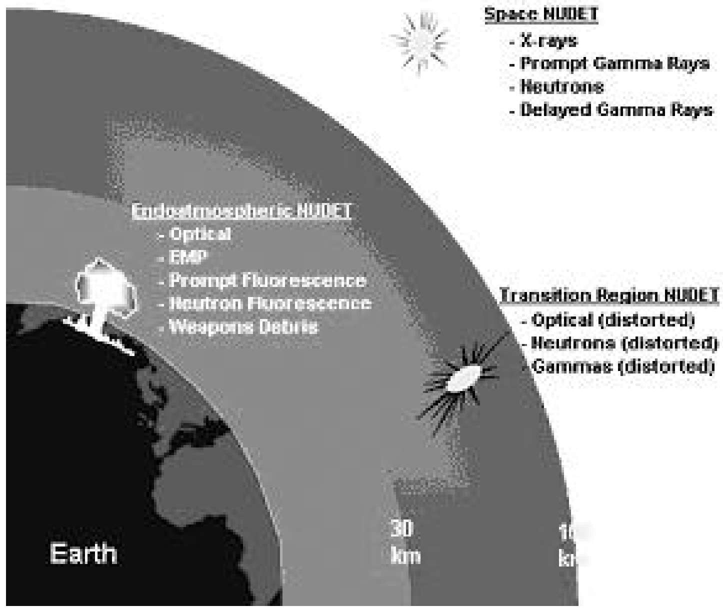


Figure 1. Nuclear Phenomenology [USNDS Project Officer Workbook]

No other atmospheric events, natural or man-made, can cause the simultaneous appearance of all these interrelated phenomena in such a precisely predictable time sequence.

For up to a minute after a nuclear detonation, energy in the forms of radiation, EMP (electromagnetic pulse), light, heat, sound, and blast are released in all directions. The detectable characteristics of these emissions are governed by the surrounding environment, as well as the weapon's design and material composition. Sensors aboard GPS satellites are capable of detecting light, EMP, and radiation in the form of x-rays, gamma rays, and neutrons. The phenomenology detected is highly dependent upon the altitude of the nuclear explosion. The nuclear phenomena is detected by the satellite sensors, downlinked to the USNDS ground segment, and processed [DOE National Security Profile, 86].

GPS

Most GPS users are unaware that the satellites serve a role other than navigation. In addition to carrying the navigation and timing payload, the satellites carry a payload that enables them to detect nuclear weapons bursts. Starting with the launch of satellite vehicle 8 (PRN 11), the GPS satellites have formed an important component in the U.S. arsenal for monitoring compliance with the nuclear weapon Non-Proliferation Treaty. The fact that the GPS satellites have the capability to detect nuclear detonations has been neither classified nor well advertised [Parkinson, 36].

The Nuclear Detonation (NUDET) Detection System (NDS) provides a worldwide, highly survivable capability to detect, locate, and report any nuclear detonations in the earth's atmosphere, near space, or deep space in near real-time. The NDS consists of space, control, and user equipment segments [USNDS Strategic Plan, 2].

The space segment consists of NUDET detection sensors on the GPS and Defense Support Program (DSP) satellites. The control segment consists of ground control hardware and software known as the Integrated Correlation and Display System (ICADS). The user equipment segment consists of the Ground NDS Terminals (GNT). NDS supports NUDET detection requirements for Air Force Space Command (AFSPC) Integrated Tactical Warning and Attack Assessment (ITWAA), United States Strategic Command (USSTRATCOM) Nuclear Force Management, and Air Force Technical Applications Center (AFTAC) Treaty Monitoring. Figure 2 illustrates the flow of data from the space segment to the control and ground processing segments to the users.

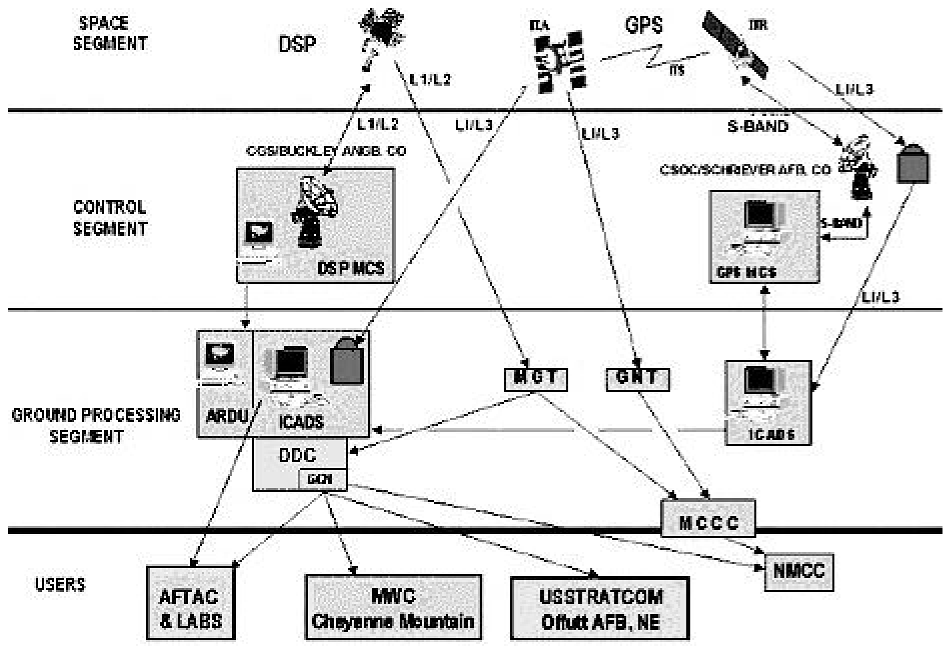


Figure 2. USNDS Overview [USNDS Project Officer Workbook]

NDS Components

The prime component of the NDS subsystem onboard GPS satellites is the Global Burst Detector (GBD) containing a suite of detectors and a sensor data processor. All GBDs host a BDY optical sensor (bhangmeter). Most also have a BDX X-ray sensor, and many of the GBDs support the BDW sensor to detect an electromagnetic pulse. Satellite communications are accomplished via the Integrated Transfer Subsystem (ITS). Figure 2 illustrates the various NDS components [USNDS Project Officer Workbook].

The bhangmeter (BDY) is a non-imaging radiometer responding to optical signals generated by NUDET fireballs. It consists of a light-collecting lens with a 30-degree primary field-of-view (FOV), a non-metallic conical sunshade, a three-segmented photo diode sensor, and an electronics subsystem. Because the satellite will periodically pass into and out of eclipse, a "solar inhibit" function disallows BDY data processing to

prevent the BDY from creating false events due to viewing of the sun [USNDS Project Officer Workbook].

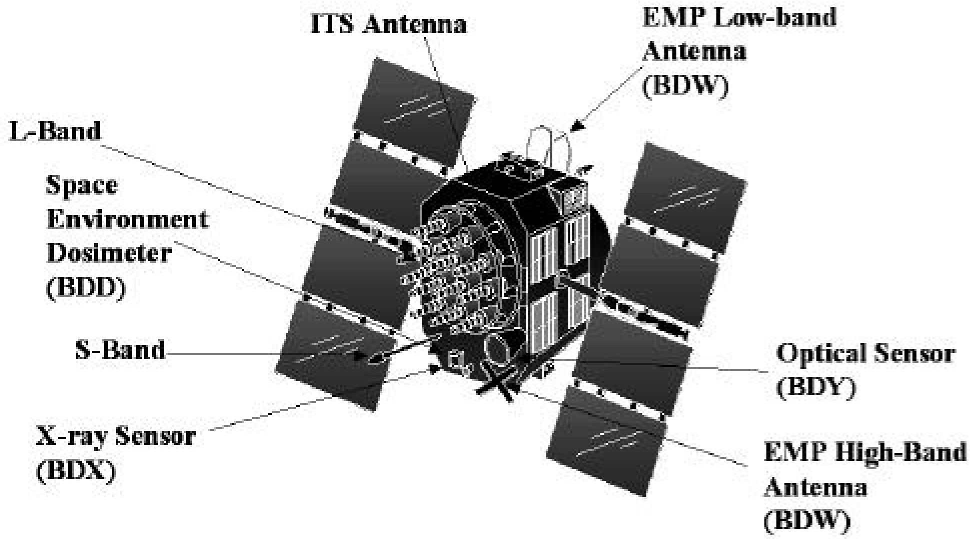


Figure 3. NDS Subsystem Components [USNDS Project Officer Workbook]

The Burst Detector Processor (BDP) is the functional interface between the detectors and the satellite. It primarily provides power, timing, commanding, and data processing and transfer for the detectors and the satellite communications processors [USNDS Project Officer Workbook].

The BDX, or X-ray sensor, samples the X-ray energy spectrum in four spectral bands to detect nuclear detonations. The function of the BDX is detection and location in the high altitude endo- and exo-atmospheric arenas [USNDS Project Officer Workbook].

The W-Sensor Receiver/Processor, or also known as the EMP sensor (BDW) provides data in the endo-atmospheric arena. It monitors the atmosphere for the electromagnetic pulse from a nuclear detonation. The BDW is also slaved to the bhangmeter (BDY), meaning a signal is declared, by the BDP, only when a BDY signal is detected within a coincidence window. Slaving helps make the initial determination

that a NUDET has occurred, and then provides time-tagging, characterization, and location information [USNDS Project Officer Workbook].

As with any mechanical component, the various NDS sensors are subject to degradation and failure over their useful lifetime. The state-of-health of the satellite as well as each of the critical NDS components onboard are recorded several times daily. The corresponding data is often illustrated in a format similar to the GPS/NDS status chart found in Appendix A. This chart clearly illustrates planar distribution of satellites, which satellites are spares, and specific component status. The actual state-of-health of the constellation is CLASSIFIED.

Satellite Constellations

The use of multiple satellites, forming a constellation, provides an effective means to gain satellite coverage over the entire globe. The coverage of the Earth's surface by the multiple-satellite systems has been studied by J.G. Walker and many other researchers. These studies have mostly been confined to satellites following multiple circular orbits of equal period, providing continuous multiple coverage of the entire surface of the Earth. Elliptical orbits appear less suitable than circular orbits for whole-Earth coverage as opposed to regional coverage. Moreover, only satellites in a common circular orbit can maintain station relative to none another continuously as they move around this orbit [Wang, 968].

The Walker Delta Low-earth-orbit satellite network was first proposed and investigated by Walker in the early 1970's. It represents a general class of circular orbit satellite constellations with equally spaced satellites and orbit planes. In this family of

constellations, there are T total satellites in P uniformly spaced planes of circular orbits, each plane at the same inclination with respect to the equatorial plane. There are T/P uniformly spaced satellites in each plane. The relative phasing between satellites in adjacent planes is given by F, which is in units of 360 deg/T. Hence, when a satellite in any plane is at its ascending node, there is a satellite in the adjacent plane having a more easterly ascending node [Walker, 370].

Walker has shown that continuous worldwide coverage with at least six satellites in view everywhere is possible with 24 satellites in six planes using a 24/6/1 constellation at an inclination angle of 57 deg for users with a minimum elevation angle of 7 deg. The selected GPS-24 satellite constellation is shown to give fivefold visibility. Although it does not have as good a full constellation satellite visibility as the (24/6/1) constellation, the GPS-24 satellite constellation has instead been selected based on the basis of best coverage if a single satellite becomes inoperative [Parkinson, 42]. Figure 4 illustrates the location of the GPS satellites for the initial 24. Each plane contains four satellites. Three of the four satellites in each plane are active and spaced approximately equidistantly. One satellite in is designated as a spare and located adjacent to an active satellite [USNDS Project Officer Workbook].

Most constellations aim to provide the users with a continuous reliable service or at least a minimum level of service. When one satellite fails to operate, the remaining satellites are required to provide needed services at a comparable level. Three approaches to performing satellite replacements are: 1) placing spare satellites in the constellation, 2) placing spares in parking orbits, or 3) keeping spare satellites on the

ground [Cornara, 2]. As seen in Figure 4, the GPS constellation was designed to include spare satellites within the constellation.

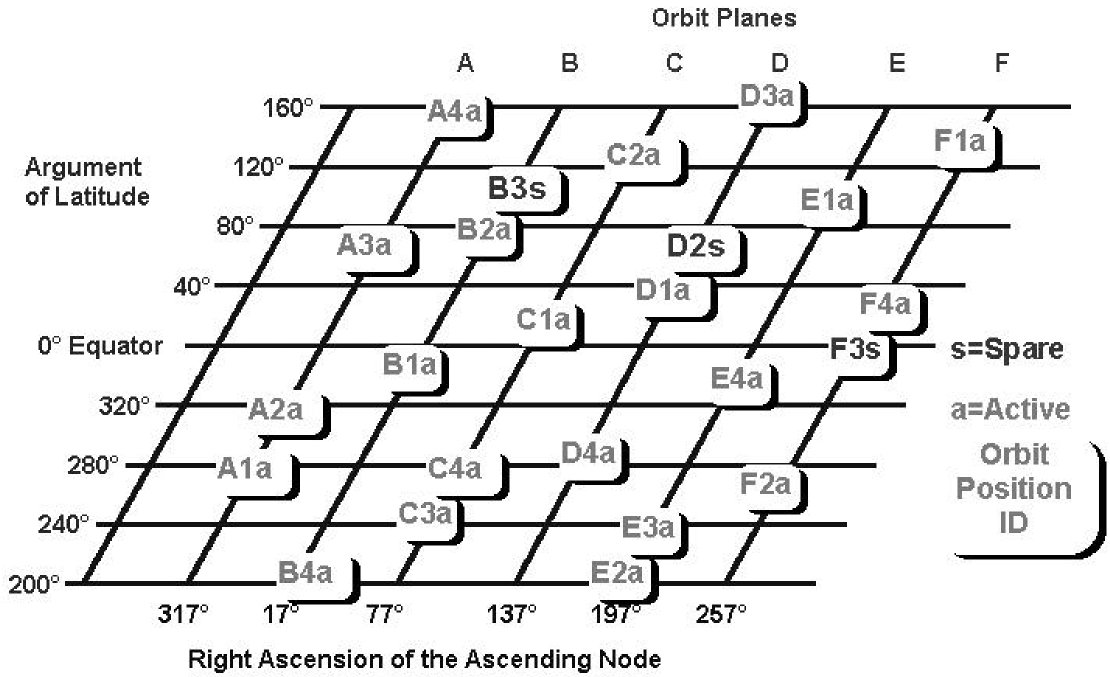


Figure 4. Representation of GPS-24 Constellation [USNDS Project Officer Workbook]

GPS Constellation

The GPS constellation currently consists of three versions of GPS satellites (Block II, Block IIA, and Block IIR). The current operational constellation consists of 4 Block II, 18 Block IIA, and 6 Block IIR satellites. The Block II satellite was designed to provide reliable service over a 7.5 year life span [Parkinson, 65].

The satellites have a period of 12 hours sidereal time and a semi-major axis of 26,561.75 km. A sidereal day is defined as the time for the Earth to complete one revolution on its axis in Earth-Centered-Inertial (ECI) space and consists of 24 sidereal hours where 1 sidereal day is slightly shorter than a mean solar day. One sidereal day is

23 hr, 56 min, 4.009054 s. Their orbital period is approximately 11 hrs 58 minutes, so that each satellite makes two revolutions in one sidereal day (the period taken for the earth to complete one rotation about its axis with respect to the stars). At the end of a sidereal day, the satellites are again over the precise same position on earth. Reckoned in terms of a solar day (24hrs in length), the satellites are in the same position in the sky about four minutes earlier each day. The orbit ground track approximately repeats each day, except that there is a small drift of the orbital plane to the west (-0.03 per day) [Parkinson, 180].

The ground trace is the line generated on the Earth's surface by the line joining the satellite and the Earth's center as both the satellite moves in its orbit and the Earth rotates. Because the satellites have precisely a 12-hour (sidereal time) orbit, each satellite traces out exactly the same track on the Earth's surface each sidereal day. A user at any fixed point sees exactly the same pattern of satellites every day. However, because the user's clock time is mean solar time rather than sidereal time of the satellite period, the user sees this satellite pattern appear approximately four minutes earlier each day [Parkinson, 184].

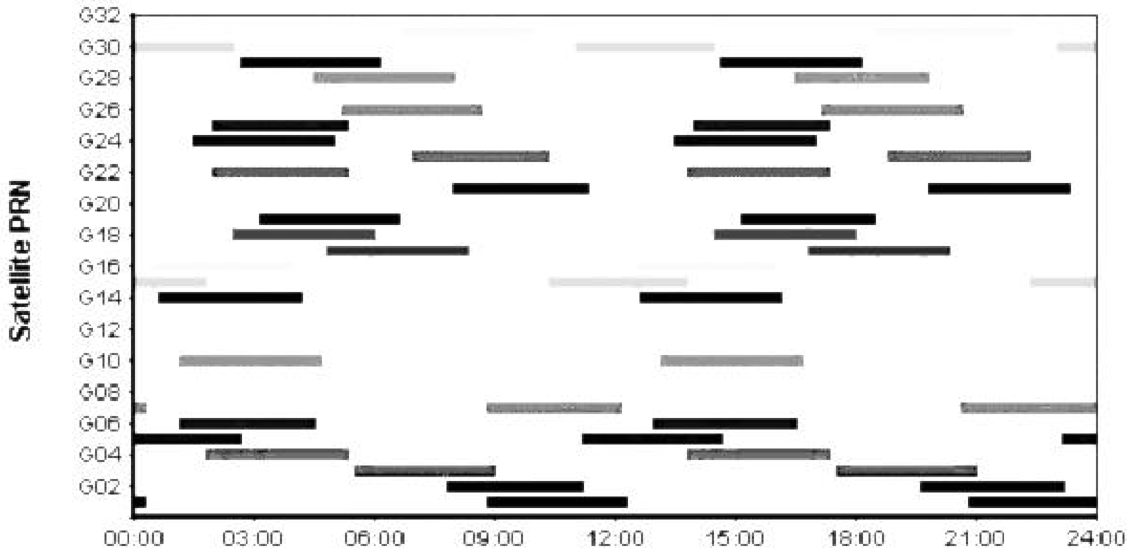


Figure 5. Satellite Visibility at Fixed Point [STK]

Figure 5 illustrates which GPS satellites are visible from a fixed location over a 24 hour period. The set of observable satellites continually changes. A satellite is generally in view for a period of approximately 3 hours at a time.

Communications

The Integrated Correlation and Display System (ICADS) is the primary component of the ground processing segment of the NDS ground system. Its function is to process the sensor data to identify and report nuclear detonations in support of the mission requirements. The ICADS antenna scheduler algorithm computes a plan for managing the assignment of antenna and receiver resources to accessible GPS satellites (those satellites above the local horizon by a specified elevation angle). The ICADS system uses antenna/receiver hardware to monitor the L-Band data. The antennas are electronically steered and capable of establishing simultaneous receive-only connections with up to six GPS satellites. This has proven to be a limitation since often times there

are more than six satellites in view of the antenna. Limiting the number of satellites the antenna can monitor restricts the number of downlink paths, possibly excluding real-time information from certain satellites [Hogg, 1].

The GPS L3 link operates as needed to transfer NDS data from the GPS satellites to the ground station. It uses time-division multiplexing with twenty-four timeslots, each lasting for 1.5 seconds. Thus, there is a 36 second transmission cycle during which each satellite has one opportunity to transmit its NDS data to the ground station. This capability is the backbone behind the problem. The ICADS system was only designed to accommodate data from 24 satellites. Currently, there are 28 operational GPS satellites capable of providing NDS data. In addition to transmitting its own L3 data during its assigned timeslot, each satellite will immediately retransmit on L3 any data that it receives from another satellite (during that satellite's assigned time slot) via a UHF cross-link [Hogg, 3].

A satellite is accessible to the ground station when it is above the local horizontal plane by a specified elevation angle. The elevation angle constraint is a conservative estimate of the ability to reliably receive data from a satellite, and depends on: 1) transmitter power, 2) transmitter and receiver antenna gains, 3) channel parameters such as quiet or scintillated atmospheric conditions, and 4) the presence of noise sources. The number of satellites accessible to the ground station varies over time as the satellites orbit the rotating Earth [Hogg, 2].

Opportunities for communications over the crosslink depend on a timing window implemented by the crosslink receiver. Following each X1 epoch (every 1.5 seconds), the receiver listens for the leading edge of a valid transmission to be detected within a

timing window that accounts for a transmitter turn-on and propagation delays. The timing window produces an acceptable range for crosslink communications of approximately 12500 to 47500 kilometers. The ability to deliver information over the crosslink also depends on several aspects of the design of the crosslink equipment, including age, transmitter power, and antenna gain (a function of the azimuth and depression angles). In Build 4, opportunities for crosslink communications were specified using the depression angle, the angle between the local horizontal plane and the line of sight to another satellite. The aspects of SATCAP that affect connectivity are the statuses of: 1) the crosslink receiver (ITSR), 2) the crosslink transmitter (ITSX), and 3) the L3 downlink transmitter (L3). Each satellite has a status for these three items, and each of these has one of four possible values: 0 (no information), 1 (red), 2 (yellow), 3 (green). The scheduler assumes a connection is possible only when the relevant hardware status is “GREEN” [Hogg, 3].

There are a number of issues that affect the availability of a path from a source satellite to the ground station. First, the source satellite must have an assigned NDS timeslot. For the direct path the source satellite’s downlink transmitter (L3) must be operational, the satellite must be accessible to the ground station, and it must be selected for tracking. For the indirect paths the source satellite’s crosslink transmitter (ITSX) must be operational and a relay satellite must have an operational crosslink receiver (ITSR), must be configured to receive from the source satellite, must have an operational downlink transmitter, must be accessible to the ground station, and must be selected for tracking [Hogg, 4].

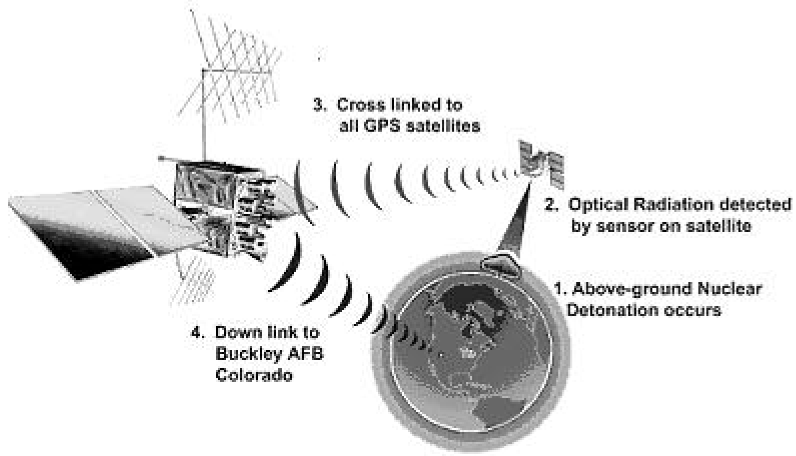


Figure 6. Satellite Communication [USNDS Project Officer Workbook]

The GPS system supports up to 32 satellites for the navigation function, but as explained previously the NDS communications system provides timeslots for only 24 satellites. Those GPS satellites that do not have a timeslot have no value as a data source. The value of specific satellites can be decreased if they have faulty NDS sensors or other problems [Hogg, 6].

Computing Coverage

GPS/MS is a classified modeling and simulation program capable of providing a variety of information regarding the coverage associated with the GPS constellation. The logic code was written in C++ programming language with an interface to IDL for graphical outputs and user interface. The basis for evaluating coverage lies in reducing the surface of the earth to a series of equally spaced grid points and evaluating coverage at each grid point at time steps for the entire simulation time. The results for all grid points are then combined to reveal a numerical value for global coverage. A coverage

value of 26 indicates that an average of 26% of the grid points are coverage for the simulation period [GPSM/S].

Prior to simulation, orbital data and state-of-health inputs for the 24 satellites monitored by NDS are read into GPS/MS from a current ICADS file. China Lake almanac files were used to gather the orbital data for the spares satellites since they are not actively tracked by ICADS [http://sirius.chinalake.navy.mil/almanacs.html].

The simulation determines coverage at each grid point for the specified 24-hr period. The default settings have a grid point every 2.5 degrees. Over the entire surface of the earth, there are a total of 10585 points. Coverage is calculated every 15 minutes for the specified day leading to a total of 96 time steps. For each grid point and each time step, GPS/MS determines the satellites in view, their ability to detect an event as specified by the mission requirements, and the ability of the satellites to relay the information back to the ground station [GPSM/S].

Use of GPS/MS was limited due to its classification of SECRET. The consequences of this restriction were eased by the availability of Satellite Took-Kit (STK). STK is a simulation model provided by Analytical Graphics Inc. (AGI). The specific inputs in GPS/MS could not be modeled exactly in STK. However, STK proved to be a valuable substitute when GPS/MS was not available.

Previous Research

Extensive documented research exists describing the use of genetic algorithms to construct satellite orbits that will maximize global coverage while minimizing the number of satellites employed [Confessore, 1]. There are a number of applications for

satellites including cellular telephone networks that depend on large satellite coverage areas. Through a constellation of 66 low earth orbiting satellites, the Iridium Satellite System delivers essential communications services to and from remote areas where ground based communications are not available [Confessore, 2]. Cellular phone communications infrastructure is aided by the presence of numerous local ground stations to relay data. However, in the case of NDS coverage, all event data must be relayed to a single ground station in real-time for processing. This requirement severely constrains the NDS problem and makes the communications link infrastructure critical.

The analysis of failure configurations of satellites and the influence of the failure of satellites to coverage performance of a constellation is rarely reported. Chan-Wang Park analyzed the coverage performance of satellite constellations in low earth orbits [Park, 1]. In Park's research, the performance of constellations was evaluated based on the maximum non-visibility time at one receiver position on earth by using simulation software. Maximum non-visibility time was compared to the configuration of failure of satellites to establish the worst case combination of failures in a satellite constellation. Park also examined the effects of phase changing to reduce the degradation of performance. Lateral and longitudinal failures were explored. Longitudinal failures referred to failure of more than one satellite in series within a plane. Lateral failures are the failures of two satellites in adjacent planes. The significant results were that longitudinal failures had the greatest effect and overall performance is enhanced with a phase changes to close the planar gaps [Park, 6].

Knapsack Problems

Consider the problem of preparing for a hike. You can only bring those items that fit into your backpack. Unfortunately, you have more things that you want to bring than can fit into that backpack. You are faced with the problem of selecting those items to maximize their utility on the hike and not exceeding the volume limits of the backpack. This is known as the knapsack problem [Martello and Toth]. This type of problem falls into the category of mathematical programming problems called integer programming problems, more specifically binary integer programming problems (BIP). BIPs derive their name from our use of decision variables taking on values of 0 or 1 to represent a binary condition: on/off, select/non-select, yes/no. In the case of the knapsack problem, the binary decision variables represent selection of the item and inclusion in the knapsack (value of 1 assigned), or rejection of the item (value of 0). When selected, that item adds value (its associated p_j) to the objective function and consumes knapsack resource (it's w_j coefficient) from the constraint. The knapsack constraint cannot be violated. Mathematically, the problem has the following form:

$$Maximize \qquad \sum_{j=1}^{n} p_j x_j$$

Subject to:

$$\sum_{j=1}^{n} w_j x_j \le b$$

$$x_j \in (0,1)$$

where p_j is the value of placing item j into the knapsack, w_j is the cost (amount of resource used) when item j is placed in the knapsack, and b is the total resource available in the knapsack [Martello and Toth, 156].

While simple in form, this combinatorial problem can be difficult to solve to optimality in practice. Thus, as with many BIPs, non-optimal algorithms, or heuristics, are employed. One naïve approach is to simply add item randomly until no more are allowed by the knapsack constraint. A slightly better approach is to simply choose those items with the smallest a_j values, again until no more are allowed by the knapsack constraint. Another approach is to choose those items with the largest c_j values, again until no more are allowed by the knapsack constraint. The better heuristics account not only for the value of the item, but also the relative cost of that item [Martello and Toth, 156]. An item's "bang" for "buck" is represented by the ratio (p_j/w_j).

A more specialized form of the knapsack problem is the multiple choice knapsack problem [Martello and Toth, 157]. The multiple choice knapsack problem is defined as given a set of n items and a set of m knapsacks ($m \le n$), with

p_j = profit of item j,

w_j = weight of item j,

c_i = capacity of knapsack i,

$$\begin{aligned}
&\textit{Maximize} \quad z = \sum_{i=1}^{m}\sum_{j=1}^{n} p_j x_{ij} \\
&\textit{subject to} \quad \sum_{j=1}^{m} w_j x_{ij} \le c_i, \quad i \in M = \{1,\ldots,m\}, \\
&\qquad\qquad \sum_{i=1}^{m} x_{ij} \le 1, \quad j \in N = \{1,\ldots,n\}, \\
&\qquad\qquad x_{ij} = 0 \textit{ or } 1, \quad i \in M, j \in N, \\
&\textit{where} \\
&\qquad x_{ij} = 1 \textit{ if item } j \textit{ is assigned to knapsack } i; \\
&\qquad\quad 0 \textit{ otherwise}.
\end{aligned}$$

When m = 1, the multiple choice knapsack problem reduced to the single knapsack problem [Martello and Toth, 157]. For this application, each orbit plane could represent a unique knapsack (m = 6). The capacity of each knapsack, c_i, is the maximum possible number of satellites in each respective plane. Variations of the model are possible. The difficulty with fitting this application to a multiple choice knapsack format is assigning benefits for each of the satellites. An individual satellite's independent contribution to global coverage is difficult to quantify.

In this application, a satellites profit is gauged by its ability to detect nuclear detonations and relay the data back to the ground station. Penalties could be assigned to satellites with degraded states of health or constellations with sparse orbit planes.

Heuristics

A heuristic method is a procedure for solving problems by an intuitive approach in which the structure of the problem can be interpreted and exploited intelligently to obtain a reasonable solution. There are several instances where the use of heuristics is desirable and advantageous. The most common of these is when an exact method may be available but is computationally unattractive due to the excessive time and/or storage requirements. In general, and without regard to a specific problem, a good heuristic should have the following qualities and features:

- Simplicity, which facilitates user understanding and acceptance.
- Reasonable storage requirements.
- Accuracy

- Robustness – the method should obtain good solutions, in reasonable times for a wide variety of problems and not be too sensitive to changes in parameters

- Produce multiple solutions (ideally in a single run). This allows the user to select the result that is most accurate or satisfying.

Problem dependent heuristics, that take advantage of the special structure of a problem, are more efficient than general mathematical programming heuristics, but their use is limited to the specific class of problems for which they were developed [Barr, 12].

Evaluating Heuristics

"There are two ways to study the performance of heuristics. One is analytical and relies on the methods of deductive mathematics. The other is empirical and uses computational experiments" [Hooker, 33]. In choosing test problems to evaluate a heuristic, the most obvious pitfall is to generate random problems that do not resemble real problems. Most computational experiments measure solution quality and running time. Although no set standards exist for publishable heuristic research, it is generally accepted that a heuristic method makes a contribution if it is:

- Fast – producing high-quality solutions quicker than other approaches;

- Accurate – identifying higher-quality solutions than other approaches;

- Robust – less sensitive to differences in problem characteristics, data quality, and tuning parameters than other approaches

- Simple – easy to implement

- High-impact – solving a new or important problem faster and more accurately than other approaches

- Generalizeable – having application to a broad range of problems

- Innovative – new and creative in its own right

Essentially, most researchers and practitioners wish to answer the following questions when testing a heuristic on a specific problem:

- What is the quality of the best solution found?
- How long does it take to determine the best solution?
- How quickly does the heuristic find good solutions?
- How robust is the method?
- How "far" is the best solution form those more easily found?
- What is the tradeoff between feasibility and solution quality? [Hooker, 37]

When possible, the heuristic solutions obtained should be compared to the optimal solutions. Generally, the percent deviation from optimality is reported. The rate at which heuristics converge to a solution close in value to that of the best found solution should be measured. A heuristic that can obtain an excellent solution for only once instance of a problem is not robust and arguably not very interesting. Robustness is based on the ability of a heuristic to perform well over a wide range of test problems [Barr, 10].

This chapter was devoted to summarizing the key background issues in literature supportive of this research. Included was a brief overview of the physical characteristics of a nuclear detonation and the history regarding the use of space-based sensors to monitor such events. The process by which GPS satellites are utilized as a platform to detect and report nuclear events via the NDS infrastructure was described in detail. A summary of previous research regarding satellite constellation design and the impacts of

satellite failures within a constellation was provided. Finally, operations research techniques related to solving this class of problem were reviewed. Chapter 3 is dedicated to applying the insight gleaned from the literature to solution methodology.

III. Methodology

Introduction

At first glance, determining the optimal solution to the NDS problem appears to readily lend itself to a deterministic solution via a classic knapsack problem structure. However, quantifying the value c_j, the contribution of each satellite, is not an easy task. Many of the critical parameters related governing satellite value numerically quantifiable, yet others, such as the value of a satellite's orbital location are difficult to effectively quantify. The value of an orbital location is dependent on where the other satellites are arranged within the constellation. For each unique combination of 24 satellites selected for NDS coverage (there are over 590,000 combinations) there is a unique value for each orbital location. The prospect of enumerating all combinations of 24 satellites to determine the value of each satellite's orbital location is an unattractive, computationally intensive option. Because accurate event reporting depends on reporting by multiple satellites, the arrangement of satellites in orbit is critical to maintaining global coverage. Failure to include the influence of an orbital location parameter into the model was not an option. A heuristic approach was selected based on this uncertainty and previous research that has offered insight into the effects of satellite failures within a constellation [Park, 1].

General Approach

The issue of selecting 24 satellites to maximize NDS global coverage can be represented by the following knapsack linear programming problem:

$$Maximize \quad \sum_{j=1}^{n} c_j x_j$$

Subject to:

$$\sum_{j=1}^{n} x_j \leq b$$

$$x_j \in (0,1)$$

Where:

c_j = value of satellite *i*
b = 24

The single constraint limits the contents of the knapsack to 24 satellites. For this application, each satellite has an equal weight of one unit. Therefore, while maximizing satellite value, the resource (24 satellites) will be exactly used up and thus represent the optimal solution. However, the solution to is only as good as the representation of satellite value. Determining how to effectively quantify a satellite's value is not trivial.

A satellite's individual state of health is readily quantifiable, but assessing the interaction among satellites is difficult due to the constant movement of satellites [Parkinson, 186]. Inter-satellite dependency for communications cross-links restricts a satellite's value from being independent. Cross-link and downlink structures constantly change. It is difficult to accurately account for inter-satellite interaction with out enumerating all possible combinations of solutions (over 590,000). Walker's work highlights the importance of consistent distribution of satellites between and within the planes for obtaining multiple satellite coverage over the entire globe [Walker, 560]. The overall objective of maximizing global coverage can be effectively reduced to two sub-objectives: 1) maximize the sum of satellite value and 2) minimizing orbital gaps created by satellite voids.

A heuristic was developed that begins with an optimal knapsack solution in terms of satellite value; unrestricted by satellite orbital location. The heuristic then proceeds in an iterative manner, replacing satellites until orbital gaps are minimized and inter-planar parity is achieved. The fundamental premise guiding the heuristic is that establishing an effective proxy for satellite value that incorporates all critical parameters is computationally challenging.

Satellite Value

In a knapsack LP, each item available for selection is associated with a coefficient indicating its value, utility, and/or an incurred penalty incurred for inclusion in the knapsack. Previous research at Sandia National Laboratories involving spare satellite analysis attempted to associate penalties with satellites based on sensor and communication component failure [Stuart]. The penalties were generated from empirical results. Though the penalty system has not been formally recognized as a means for decision making, the results are useful as indicators of the relative weight of various system failures. Table 1 contains a sample of penalties assigned for various component failures.

Table 1. Penalties

Component Failure	Penalty
L3	4
ITSX	8
ITSR	2
BDY	7

A satellite's total penalty is assessed by summing the penalties of all component failures. The penalty assignment system is easy to quantify, but is not a comprehensive

assessment of satellite value. While it may be effective, it should be reviewed for its scientific rigor and merit. A few discrepancies with this approach are readily apparent. First, all healthy satellites are assigned a penalty of zero and thus have a numerically equivalent value. Second, the same component failure on separate satellites is reflected by the same penalty, yet the failure's effects on overall coverage might not be equal. For example, one satellite's L3 might be more important than another because it is in view of the ground station for a longer period of time. The penalty system only addresses component failures and does not account for satellite value based on orbital location. In addition, BDY sensor degradation based on lens darkening effects was not taken into consideration [GPS/MS].

Despite the existence of a number of parameters that have a role in determining a satellite's individual contribution to global coverage, the two overriding forces governing coverage rest in the optical sensor's ability to observe an event and the subsequent ability to communicate what the sensor observes. A satellite's contribution to coverage can be effectively reduced to a function of three critical parameters: real-time connectivity (RTC), optical sensor sensitivity, and orbital location.

BDY Sensitivity

The satellite's ability to optically detect a nuclear event is related to the sensitivity of the BDY sensor. BDY sensitivity, O_i, is dependent on satellite block type (II, IIA, IIR) and sensor degradation. Both block II and block IIA satellites are equipped with the same BDY sensor, while the BDY onboard block IIR satellites is an improved version of

the sensor. The approximate ratio of the difference in sensitivity of the block II/IIA and block IIR sensors is 13 to 17 [Christiansen].

Once in orbit, the BDY is subject to a lens darkening effect that may be due to environmental conditions. Regardless of the cause, the lens-darkening effect that takes place reduces sensor responsiveness. The degree to which the lens-darkening effect has degraded the sensor is represented by a value termed responsivity (Christiansen).

Responsivity is determined by observing the trends related to the current necessary to compensate for a fully illuminated earth. When exposed to anything other than a completely dark earth, the BDY sensor must compensate for the background lighting. Compensation current is measure several times per day. Years of accumulated data has allowed the lens darkening effect to be quantified. Responsivity is represented by a unitless value between 0 and 1.0. A value of 1.0 indicates that the lens has not suffered from the darkening effect, while a value of 0.5 would indicate a 50% reduction in responsiveness. A block IIR BDY with a 0.765 responsivity value has a sensitivity value equivalent to a block II/IIA BDY with a responsivity of 1.0 [Christiansen].

Real-time Connectivity (RTC)

Real-time connectivity (RTC) was established and defined as the number of hours a satellite is in communication with the ground station (either directly or via a cross-link) over a 24-hour period. This value provides a means to quantify communication system failures within the constellation. A semi-synchronous orbit dictates that the satellites will trace the exact same ground track every twenty-four hours. Therefore, a satellite's real-time connectivity is consistent every 24 hours.

Satellite Tool-Kit (STK) was used to compute RTC for each of the operational satellites and the notional satellites from the test cases. STK is an independently validated and verified commercial simulation tool widely used for aerospace applications. The chains module within STK allows the user to model these communications pathways. A chain is defined to represent a string of resources [STK v.4.2.1]. The simulation is used to assess the amount of time a chain is connected over a 24-hour period. RTC can be determined by evaluating two chains:

Chain 1) Direct-link chain (ground station – satellite) and

Chain 2) Cross-link chain (ground station – x-link satellites – satellite).

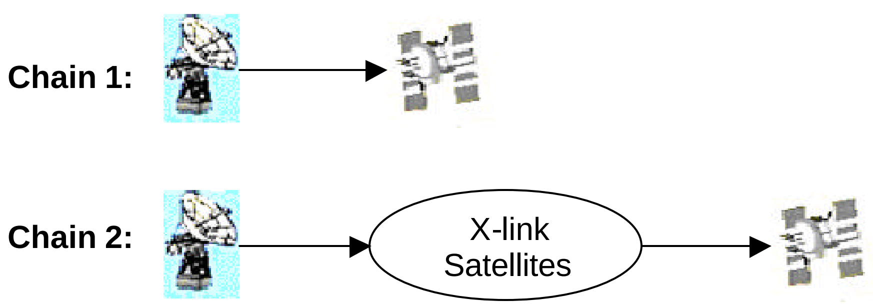


Figure 7. RTC Chains

The ground station is defined by the location of Denver, Colorado (39:40:00N, 104:57:00W). The "x-link constellation" resource is the set of satellites capable of cross-linking (healthy ITSR and L3 components). Table 2 indicates the how RTC is computed given the possible failure modes.

Table 2. ITS Component Failure Implications

Component Failures	Real-time Communication Implication	RTC (hours)
ITSX	Contributes individually when directly ground linked via L3. Serves as a viable x-link option.	Chain 1
ITSR	Useless as x-link. Individual contribution when connected.	Chain 1 + Chain 2
L3	Useless as x-link. Only contributes when x-linked.	Chain 2

GPS/MS is the accepted modeling tool by which AFTAC calculates global coverage [Holtgrave]. To maintain consistency, STK simulations were confined by the same constraints as GPS/MS when possible [GPSM/S]. Cross-link access and satellites in-view of the ground station were restricted by depression angles and elevation angles respectively. The STK simulation period to compute RTC was limited to 24-hours, since the satellites repeat the exact same ground track over this period [Parkinson, 185]. The RTC calculations are made assuming the availability of all operational satellites. RTC is represented by a unitless, normalized value. An RTC value of 1.0 indicates continuous connectivity.

Coverage Contribution Coefficient (CCC)

The coverage contribution coefficient (CCC) was established and defined as a means to incorporate the effects of a satellites optical sensor degradation and real-time connectivity into a single parameter serving as a proxy for satellite value. CCC is defined as the product of RTC and responsivity (CCC = (RTC) x (Responsivity)). The upper bound on CCC was a value of 1.0. This number would indicate uninterrupted RTC (RTC = 1.0) and no degradation to BDY sensitivity (Responsivity = 1.0). CCC serves as a proxy for each measure, RTC and Responsivity. By combining each multiplicatively,

the interaction of the effect is approximated. While not a precise measure, CCC captures the essence of the key effects.

Value Evaluation

A pilot study was conducted to evaluate the merits of assigning CCC as a proxy for satellite value. An assumption was made that CCC would serve as a better proxy for satellite value than BDY sensitivity (O_i), RTC, or the penalty function. Greedy solutions were computed, subject to the knapsack LP definition, using the four different parameters in place of the variable c_j (CCC, O_i, RTC, and penalty). The resulting solutions were each input into GPSM/S to compute the respective global coverage.

Key Assumptions

All coverage calculations required by the heuristic were computed using GPS/MS software. The simulation software contains a number of mission specific classified parameters that are not available in other commercial software packages. The three mission areas (NFM, TM, ITWAA) specify different detection requirements with regard to event yield, atmospheric conditions, and event reporting. The Treaty Monitoring mission was selected for all simulations per sponsor input.

All regions of the globe were treated with equal importance with regard to coverage per the Operational Requirements Document (AFSPC 003-94-T). Coverage by the constellation for the simulated day was assumed representative of the coverage of the same constellation over a period of time due to the daily repetition of the ground tracks. The state-of-health for the BDW sensor was not included in the model. Since the BDW is slaved to the BDY, the state-of-health of the BDW was eliminated. The period of time

that satellites shut down to avoid the sun was neglected. The eclipse time for a satellite depends on which orbital plane it is located in. Since the eclipse season was not unique to individual satellites, it was removed from consideration.

The link-error or noisy earth model was turned off for simulations in GPS/MS. The link error model accounts for a “noisy” region of the earth where cross-link transmissions between satellites would have a reduced chance of accurate reception. Use of this option would add a source of variability when comparing solution results. This could, however, be an area for future study.

The states-of-health for the spare satellites were assumed to be the same as the last time each respective satellite was active. Once designated as spares, the NDS ground segment does not maintain state-of-health updates. This information should be accurate for component failures, however, responsivity values could be worse.

Search Heuristic

An iterative search heuristic was constructed to produce a set of solutions yielding high coverage percentages. The coverage contribution coefficient (CCC) does not completely account for all satellite effects. Satellite orbital location is not accounted for in the proxy value. Research indicates that spatial gaps or holes in constellations degrade global coverage performance. This heuristic begins with an initial solution that is selected with a greedy approach with respect to CCC. Hypothetically, the solution could leave one of the six orbital planes devoid or sparse in satellites. The heuristic seeks to improve on the initial solution by filling in the orbital gaps present in the initial solution while maintaining a highest overall total constellation CCC value possible. Satellites in

planes with more than 4 basis satellites will be replaced by spares in planes with less than 4 basis satellites. At each iteration, the highest valued spare will replace the lowest valued satellite in the basis that meeting the criteria. These replacements will proceed until the 24 basis satellites are evenly distributed among the 6 satellite planes (Step 7). Each plane will have 4 satellites in the basis. These satellites will be the best with respect to satellite value in each plane.

All coverage calculations will be made with GPSM/S. The search will allow less attractive solutions with respect to CCC to form the basis to expand the solution space. The second part of the heuristic involves local replacements in planes with spares. For those planes containing a spare, the least desirable basis satellite is replaced with the spare to examine potential improvements to the solution.

$\{B\}$: Basis (the set of 24 satellites tracked by NDS)
$\{S\}$: Spares (set of all satellites not in the basis)
If $x_i \notin \{B\}$, then $x_i \in \{S\}$
$\{B\} \cap \{S\} = 0$
$\{E\}$: Set of satellites in planes containing greater than n/6 satellites in the basis
$\{E\} \subset \{B\} \cup \{S\}$

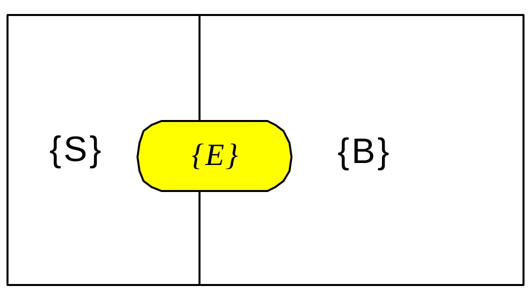


Figure 8. Satellite Sets

n = number of operational satellites
x_i = satellite i (i = 1, 2…n-1, n)
B^-: basis satellite with the lowest value w.r.t. CCC

S^+ : spare satellite with the greatest value w.r.t. CCC
$\{P_j\}$ = set of satellites in Plane j (j = 1,2,3,4,5,6)
u = iteration counter
C_u = global coverage at iteration u (computed with GPS/MS)

The heuristic begins at Step 1 with the optimal solution to the knapsack using CCC as a proxy for satellite value. This solution is not constrained by satellite orbit location. Steps 3 through 6 will attempt to improve coverage by generating solutions with increased planar parity.

Initialize counters: u = 0, j = 0

Procedure

Step 1. Initialize the basis. Assign the top 24 satellites w.r.t. CCC to $\{B\}$
Step 2. Compute C_u with GPSM/S
Step 3. Increment counter $u = u + 1$
Step 4. Replace B^- with S^+, where $B^- \in \{E\}$ and $S^+ \notin \{E\}$.
Step 5. Compute C_u with GPSM/S
Step 6. If $E \neq \{\emptyset\}$, Go To **Step 3**

(NOTE: Following **Step 6**, each of the six planes will contain an equal number of satellites in the basis, 4; representing the best 4 satellites from each plane with respect to CCC.)

Steps 7 – 13 of the heuristic dictate local replacements within each plane containing spares in an attempt to improve global coverage. If the replacement does not increase coverage, it will be rescinded.

Step 7. $j = j + 1$ and $u = u + 1$
Step 8. If $\{P_j\} \cap \{S\}$, replace P_j^- with S^+
Step 9. Compute C_u
Step 10. If $C_u < C_{u-1}$, undo the replacement in **Step 8** Go To **Step 7**
Step 11. STOP when $j = 6$

As seen in Figure 9, as the heuristic progresses, the objective of maximizing CCC is traded for the objective of minimizing orbital gaps.

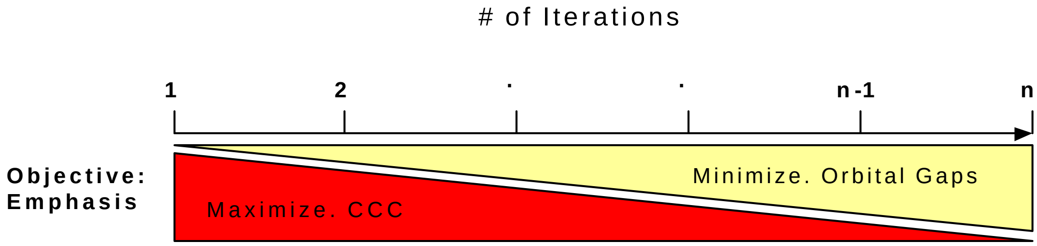


Figure 9. Objective Trade-off

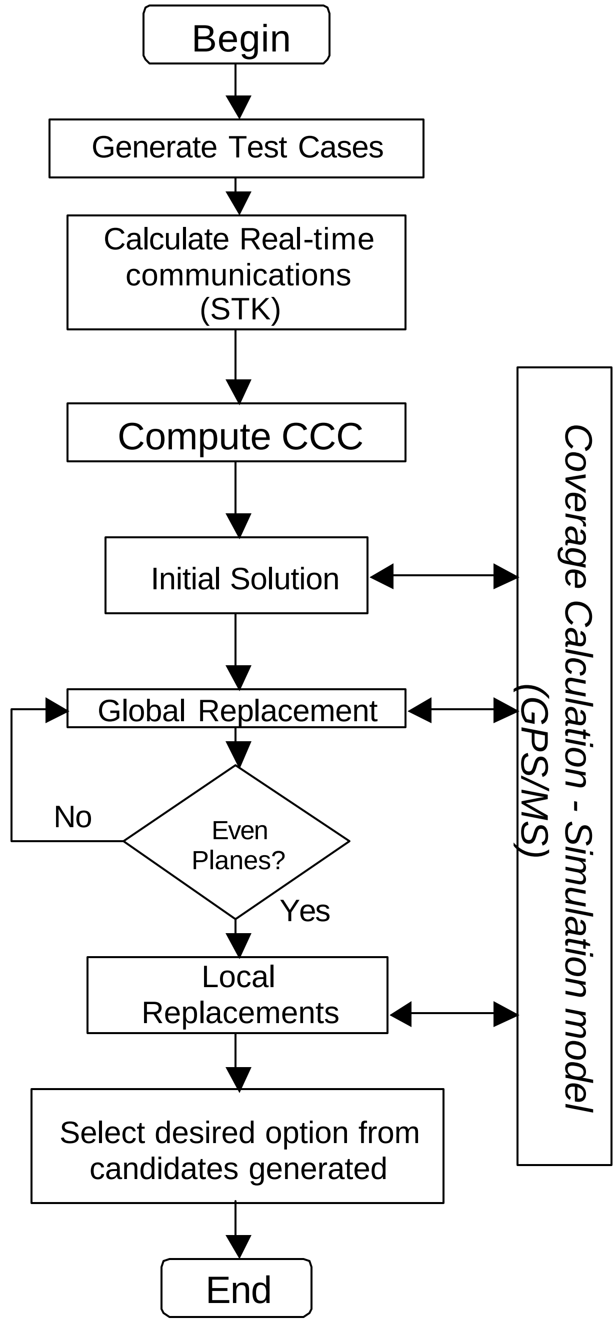


Figure 10. Heuristic Flow Chart

Computational Effort

A unique solution is generated after each iteration in the heuristic. Each solution must be inputed into GPSM/S to compute the coverage corresponding to the solution. A single simulation takes over three minutes for the model to compute. Enumerating all possible solutions for a 29 choose 24 case would require over 3 years of simulation. Enumeration was quickly ruled out as a solution technique. Due to the classification level of GPSM/S use of the software was restricted. On site access to the software was restricted to AFTAC at Patrick AFB, Florida and Sandia National Laboratories in Albuquerque, New Mexico.

Test Cases

The robustness of the heuristic was evaluated against three unique test cases. The number of satellites and their respective orbital parameters for each test case was consistent with the current GPS constellation. The state-of-health of the communications system components and the BDY responsivity were generated using reliability data obtained from SNL. The reliability of each satellite's communication system components (ITSR, ITSX, L3) was represented by Weibull distributions in the form

$$F(x) = 1 - e^{\left(x/b \right)^{a}}$$

where x represents time in months (Stuart). The test cases anticipate possible state-of-health changes over the next three years. Test Case 1 represents a nominal constellation state-of-health for 1 Jan 2002, Test Case 2 1 Jan 2003, Test Case 3 1 Jan 2003. Each case is generated independent of the previous case. Consistent with GPS/MS, each

component's capability will either be fully operational (represented by a 1) or degraded (indicated by a 0). Degraded systems are considered inoperable.

The sensor's lens darkening effect, varies according to block type and are approximately normally distributed for block II/IIA. Test case conditions were randomly generated from this distribution. Block IIR satellites, remarkably, have not suffered any darkening effects, therefore they all have a responsivity value of 1.0. The table below shows the format of a test case inputs.

Table 3. Test Case Format

Satellite:	*Transmitter*	*Receiver*	*Downlink*	*Responsivity*
1	1	0	1	0.809
2	1	0	0	0.758
.	0	0	1	0.867
.	1	1	1	0.681
.	0	1	0	0.010
n-1	0	0	0	0.832
n	0	1	1	0.127

The state-of-health data was inputed into STK, which will generate the real-time connectivities for the satellites in each of the test cases. Each run in STK takes approximately 10 seconds on a desktop computer.

Evaluating Results

The best coverage generated by each search was compared to the optimal coverage for the test case. The optimal coverage for each test case was computed based on a hypothetical scenario that would allow all operational satellites to contribute to coverage. It represented an idealized, unattainable solution for the current state of health. The robustness of the heuristic was evaluated based on the consistency of performance

with respect to the test cases. In order to be useful, the heuristic must return reliable results with a variety of state-of-health inputs. The results were analyzed based upon, best coverage, number of iterations to best coverage, and how close the solutions are to the optimal coverage. The results indicated which critical parameter best represents satellite utility. The number of iterations before local optimality is obtained indicates the relative importance of the satellites' distribution among the planes.

IV. Data Analysis

Overview

The heuristic technique was designed to generate a set of feasible solutions. Each solution, identified as a basis {B}, represented a unique set of 24 operational GPS satellites. The heuristic required the user to input state of health parameters for each operational satellite in the constellation. Given these inputs, the heuristic generated an initial solution and then stepped through a finite series of iterations based on one-for-one satellite replacements at each step. GPS/MS was used to compute the global coverage for the solution at every iteration.

Test Cases

The heuristic was benchmarked against three test cases prior to being applied with current state-of-health inputs. The test cases were designed to exercise the heuristic through a variety of inputs. Reliability data for satellite component failures and optical sensor degradation was supplied by personnel at Sandia National Laboratories [Stuart]. The data was used to create independent test cases simulating hypothetical constellation states-of-health for 1 January 2002, 1 January 2003, and 1 January 2004. Since new satellites continue to replace the aging constellation, propagating the current constellation state-of-health three years into the future (without replacements) provided the heuristic a worst case scenario. Only satellite state-of-health was varied for the test cases. Satellite locations for the test cases remain consistent with the actual

constellation, and are indicated by Plane (A-F) and slot (1-5). Currently, there are 28 operational GPS satellites in orbit available for NDS [Holtgrave]. Figure 11 illustrates the approximate location of each operational satellite in its respective plane. The satellites are labeled by the 4-digit inter-range operational number (IRON) followed by the plane and slot location.

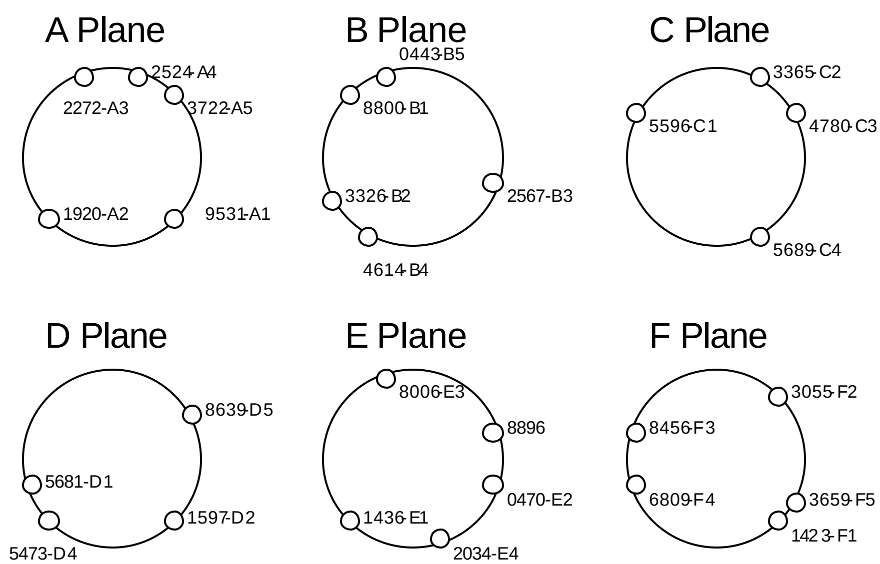


Figure 11. Satellite Planes (USNDS Project Officer Workbook)

Table 4 displays the notional state-of-health inputs for each test case. Communication components (ITSX, ITSR, L3) reliability trends follow Weibull distributions. The parameters used reflect historical data from Sandia National Labs. A "0" indicates component failure. A "1" indicates a fully functional component. Responsivity, corresponding to optical sensor degradation due to lens darkening effects, is indicated by a fractional value between 0 and 1.0. A value of 1.0 indicates no degradation. The responsivity values for block II/IIA satellites were randomly generated

from a normal distribution. Block IIR satellites have not experienced lens-darkening effects and thus all have a responsivity of 1.0.

Table 4. Test Case States-of-Health

	Test Case 1:				Test Case 2:				Test Case 3:			
IRON	ITSR	ITSX	L3	Resp.	ITSR	ITSX	L3	Resp.	ITSR	ITSX	L3	Resp.
2567-B3	0	1	1	0.663	1	1	1	0.643	1	1	1	0.757
2272-A5	1	1	1	0.576	1	1	0	0.667	0	1	0	0.631
470-E2	1	1	1	0.614	1	0	1	0.499	0	1	0	0.591
8639-D5	1	1	0	0.589	1	1	0	0.561	1	1	0	0.478
8896-E5	1	1	1	0.377	1	1	1	0.636	1	1	0	0.640
5681-D1	1	1	1	0.504	1	1	0	0.821	1	1	1	0.742
1920-A2	1	0	1	0.764	1	1	1	0.735	0	1	1	0.673
3055-F2	1	1	1	0.633	1	1	1	0.647	1	1	1	0.518
2524-A4	1	1	1	0.723	1	1	1	0.713	1	1	1	0.461
6809-F4	1	1	1	0.530	1	1	1	0.529	1	1	1	0.648
3659-F5	1	1	1	0.418	0	1	1	0.470	0	1	1	0.422
8800-B1	1	1	1	0.832	1	1	1	0.538	1	1	1	0.831
4780-C3	1	0	1	0.670	1	0	1	0.649	1	1	1	0.593
5689-C4	1	1	1	0.569	1	1	1	0.741	1	0	0	0.651
9531-A1	1	1	1	0.675	1	0	1	0.578	1	1	1	0.715
4614-B4	1	1	1	0.38	0	1	1	0.849	1	1	0	0.524
5473-D4	1	1	1	0.811	1	1	1	0.855	1	1	0	0.762
5596-C1	1	1	1	0.326	1	1	1	0.418	1	0	1	0.542
3365-C2	1	1	1	0.540	0	1	1	0.452	1	1	1	0.530
8006-E3	1	1	1	1.098	1	1	1	0.513	1	0	0	0.785
3326-B2	1	1	1	0.591	1	1	1	0.609	1	1	1	0.440
3722-A3	1	1	0	0.605	1	1	1	0.474	1	1	1	0.596
8456-F3	1	1	1	1.000	1	1	1	1.000	1	1	1	1.000
1597-D2	1	1	1	1.000	1	1	0	1.000	1	1	1	1.000
1436-E1	1	1	1	1.000	1	1	1	1.000	1	1	1	1.000
443-B5	1	1	1	1.000	1	1	1	1.000	1	1	1	1.000
1423-F1	1	1	1	1.000	1	1	0	1.000	1	1	1	1.000
2034-E4	1	1	1	1.000	1	1	0	1.000	1	1	1	1.000

Table 4 summarizes the communication component failures for the test cases. As would be expected, the number of component failures increased with the passage of time represented by each successive test case. The data from these test cases were used in conjunction with STK to compute RTC for the satellites.

Table 5. Component Failures per Test Case

	ITSR	*ITSX*	*L3*
Test Case 1	1	2	2
Test Case 2	3	3	6
Test Case 3	4	3	8

Idealized Upper Bound

One measure to evaluate the performance of a heuristic is to compare the solution value to the problem's optimum solution. Often times, however, the optimal solution is not known. For this application, the optimal global coverage from all combinations of 24 satellites is not known. It is necessary to identify an idealized upper bound with which to compare the heuristics results. An upper bound was established and defined by relaxing the constraint restricting the constellation to 24 satellites and determining the global coverage resulting if all operational satellites contribute simultaneously. GPS/MS is capable of calculating coverage based on any number of satellites. It is not restricted to simulating only 24 satellites. For the three test cases, the idealized coverage was computed by performing the simulation with all 28 satellites contributing to coverage. No combination of 24 satellites will yield a greater coverage than this upper bound. Table 6 contains the results.

Table 6. Idealized Upper Bounds for Test Cases

	Idealized Upper Bound (% coverage)
Test Case 1	55.8
Test Case 2	42.2
Test Case 3	42.8

The constellation from Test Case 1 has the greatest idealized coverage. This comes as no surprise since Test Case 1 had the least number of component failures. The results for Test Case 2 and Test Case 3 are interesting since Test Case 3 had more component failures and a greater idealized upper bound than Test Case 2. This indicates that not all component failures have an equal effect on coverage. The previously defined component failure penalty system reflects this assumption.

Value Evaluation Results

The first step in the search heuristic requires an initial solution corresponding to the optimal solution to the knapsack problem. Coverage contribution coefficient (CCC) was used as a proxy of satellite value, c_j, in the knapsack objective function (Figure 12). Prior to exercising the heuristic, simulations were performed using GPS/MS to evaluate how CCC compared to responsivity, RTC, and penalty as an indicator of satellite value. The knapsack function was solved substituting responsivity, RTC, penalty, and CCC for c_j. This procedure was repeated for each of the three test cases.

$$Maximize \qquad \sum_{j=1}^{n} c_j x_j$$

Subject to:

$$\sum_{j=1}^{n} x_j \leq 24$$

$$x_j \in (0,1)$$

Figure 12. Knapsack Function

Figure 13 illustrates the global coverage resulting from solving based on each of the individual parameters. The data labels are normalized to the idealized upper bound. The

upper bound is represented by a value of 1.0, and all other results indicate a percentage of the unattainable upper bound. Ideal coverage is represented by a coverage value of 1.0. Each result indicates the fraction of optimal coverage achieved. Recall that the ideal coverage is achieved with the use of 28 satellites. As the idealized upper bound clearly indicates, coverage could be improved if more than 24 satellites could be used. For each test case, optimizing based on CCC produced greater global coverage than selection based solely on RTC, responsivity, or penalty respectively. This confirms the supposition that a multi-dimensional parameter such as CCC would serve as a better indicator of satellite worth than the single dimensional parameters. Solving based on the penalty proposed in GPSM/S (versus CCC) corresponded to 2.4%, 2.6%, and 2.3% reductions in coverage for test cases 1, 2, and 3 respectively.

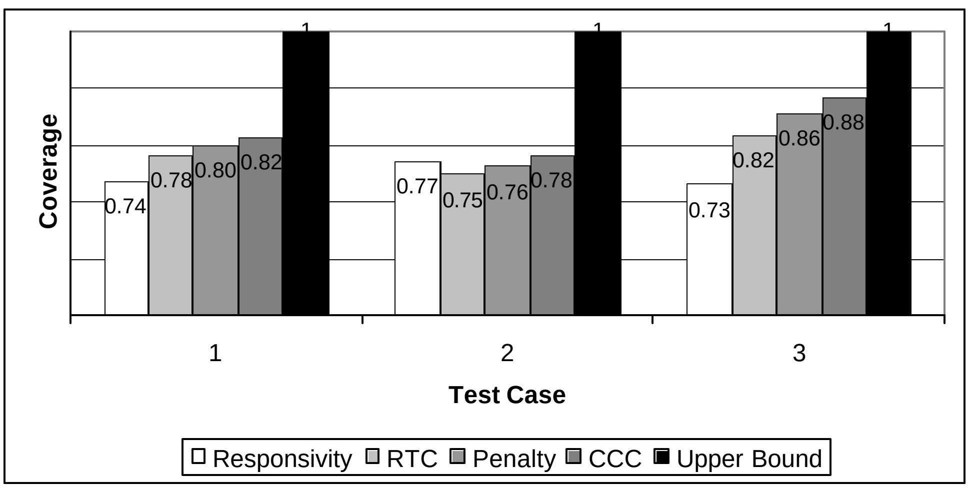


Figure 13. Value Comparison

Solving based on responsivity as an objective only addresses a single factor related to satellite performance, neglecting any consideration of communications state-of-health. Though responsivity returned a greater coverage than both RTC and penalty in Test Case 2, the results were based on the selection of satellites with high RTC. Test

Cases 1 and 3 clearly illustrate responsivity as the worst representation of satellite worth. In Test Case 3, solving based on CCC led to an excellent coverage value of 88% of the idealized upper bound.

Heuristic Progression

The best way to illustrate the performance of the heuristic is to step through an example using Test Case 1. Table 7 illustrates the progression of the heuristic for Test Case 1. Each iteration yields a unique set of satellites in the basis {B} and spares {S}. With exception of iteration 0, the basis is made up of 24 satellites indicated by a “1” and 4 spares indicated by “0”. Iteration 0 represents the unattainable upper bound for the test case of 28 satellites rather than the system requirement of 24 satellites. At iteration 0, coverage is computed with all available satellites in the basis. The upper bound in this case is 55.8%. At iteration 1, the basis is reduced to 24 satellites per NDS requirements. The solution at iteration 1 is generated by optimizing the knapsack problem with respect to CCC.

Table 7. Heuristic Progression – Test Case 1

Iteration	*9531-A1*	*1920-A2*	*3722-A3*	*2524-A4*	*2272-A5*	*8800-B1*	*3326-B2*	*2567-B3*	*4614-B4*	*443-B5*	*5596-C1*	*3365-C2*	*4780-C3*	*5689-C4*	*5681-D1*	*1597-D2*	*5473-D4*	*8639-D5*	*1436-E1*	*470-E2*	*8006-E3*	*2034-E4*	*8896-E5*	*1423-F1*	*3055-F2*	*8456-F3*	*6809-F4*	*3659-F5*
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
3	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
4	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
5	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
6	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
7	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0

After iteration 1, the heuristic's immediate goal is to add satellites to deficient planes until all planes have an equal number of satellites, while maintaining the highest total CCC value possible. A deficient plane is defined as a plane containing fewer than n/6 satellites. Table 8 indicates each satellite's rank with respect to CCC. The basis at iteration 1 includes the satellites ranked 1 through 24.

Table 8. Test Case 1 CCC Rankings

	8006-E3	1423-F1	1436-E1	1597-D2	8456-F3	443-B5	2034-E4	5473-D4	3055-F2	2524-A4	2567-B3	470-E2	3722-A3	3326-B2	5689-C4	8800-B1	9531-A1	8639-D5	2272-A5	3365-C2	3659-F5	5681-D1	8896-E5	6809-F4	5596-C1	4614-B4	1920-A2	4780-C3
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

For every basis change, the highest ranking spare meeting the criteria is added, and the lowest ranking basis satellite meeting the criteria is removed. The set {E}was established and defined as containing all basis satellites in planes containing more than 4 satellites. The set {U} was established and defined as containing all spare satellites in planes with less than 4 basis satellites. When {E} = {U} = ∅, all planes have an equal number of satellites in {B}. At iteration 1, {E} contains all satellites in planes E and F (since these planes have 5 basis satellites each). Planes A, B, and D each have four satellites in the basis while plane C has only two. At iteration 2, the lowest ranking satellite in {E}, denoted E^-, is removed from {B}, and the highest ranking satellite in {U}, denoted U^+ is added to {B}. At iteration 3, again, U^+ replaces E^- in the basis resulting in all planes containing an equal number of satellites in the basis. After planar parity has been achieved, the next phase of the heuristic aimed accounting for inter-planar interaction begins.

The premise guiding the heuristic at this phase is that a spare satellite might be in a critical orbital location as a cross-link for other satellites and lead to a greater global coverage if it replaces a basis satellite in the same plane. For each plane containing spares, the highest ranking spare replaces the lowest ranking basis satellite. If the replacement does not produce an increase in coverage, the replacement is rescinded. At iteration 4, satellite 2272 is replaced by 1920 in plane A. 4614 replaces 8800 for iteration 5. 0470 is replaced by 8896 at iteration 6, and 6809 replaces 3659 at iteration 7. The heuristic terminates after a replacement is made in plane F. Each of the replacements confined the solution to including 4 basis satellites in each plane. The solution could be adjusted to try other alternatives. It should be noted, however, that additional simulations runs would be required. The potential for possible increased coverage would have to be balanced against additional computational time. The coverage trend lines in Figure 14 illustrate the coverage resulting at each iteration in the heuristic.

Table 9 indicates the total RTC, total responsivity, total CCC, and global coverage for the solutions generated at each iteration. Between iteration 4 and iteration 5, RTC slightly increased, responsivity decreased, CCC decreased, yet the coverage increased.

Table 9. Test Case 1 Data Breakout

Iteration	Total RTC	Total Resp.	Total CCC	Coverage
0	21.11	19.39	409.18	1.00
1	19.25	17.25	332.09	0.82
2	18.93	17.39	329.13	0.75
3	18.87	17.34	327.17	0.74
4	18.42	17.53	322.87	0.69
5	18.44	17.07	314.92	0.7
6	18.43	16.84	310.31	0.67
7	18.11	16.95	306.95	0.68

The basis at both iteration 4 and 5 contain an equal distribution of satellites among the planes. Once again, this highlights the importance of satellite location as a factor contributing to coverage. Without the inclusion of this factor, it is difficult to assess the role of objective trade-off between RTC and responsivity.

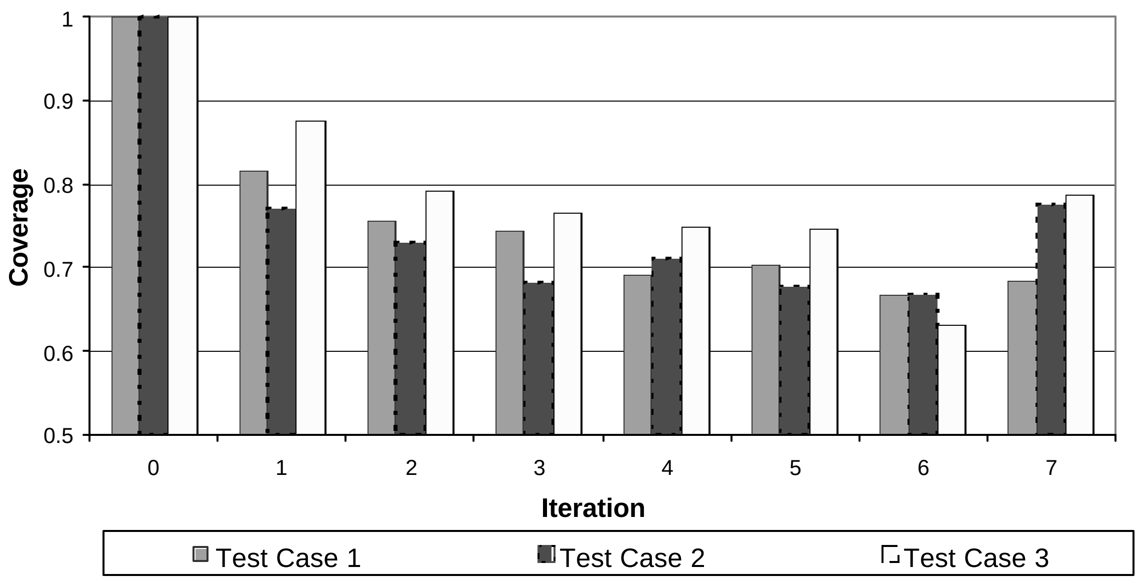


Figure 14. Heuristic Results

The coverage was normalized to the upper bound at iteration 0 for each test case. The coverage at Iteration 1 (optimized knapsack solution) was at least as high as coverage at any of the other iterations in every case as would be expected. In each of the cases, replacements made during the heuristic's progression increased the net coverage at some iteration. The most significant coverage increase occurred between iterations 7 and 8 for Test Case 3. Replacing a basis satellite with a less desirable spare (w.r.t. CCC) yielded a 8.2% increase in coverage. The coverage at iteration 8 was equivalent to the coverage at

iteration 1. The step by step progression of the heuristic for test cases 2 and 3 can be found in Appendix A.

Real Data

After evaluating the test cases, the final step was to perform the heuristic with the inputs from the constellation's current state-of-health. Each of the solutions the heuristic provided was different than the solution currently monitored by NDS. Figure 15 indicates the coverage for the solutions generated by the heuristic at each iteration compared to the coverage provided by the current constellation.

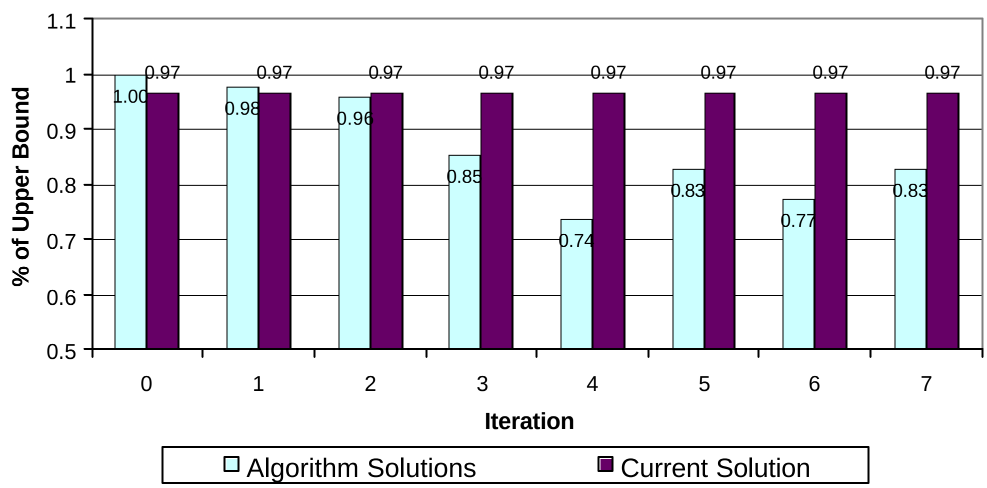


Figure 15. Heuristic Results using Real Data

The heuristic produced a solution yielding greater coverage than the current solution at iteration 1 and a solution approximately equal to the current coverage at iteration 2. The current solution does not contain the best 24 satellites with respect to CCC. Greater global coverage can be obtained from the resources available by selecting satellites based on CCC. The solutions at iteration 1 and 2 indicate two unique constellations that yield

high coverage. Having multiple solutions yielding high global coverage provides the decision maker with flexibility.

The heuristic indicates that global coverage can be improved by altering the set of 24 satellites currently being monitored. Exchanging one of the current basis satellites for a spare provides a 1% increase in coverage with respect to the idealized upper bound. Both the current solution and the best solution from the heuristic are close to the upper bound coverage. The solution at iteration 2 also provided a solution yielding a high coverage. This indicates that for some constellations, alternate optimal solutions may be present. Since the NDS portion of GPS represents a secondary mission, such alternate solutions may be important for when the first choice solution is not available.

Though individual component failures on satellites do not have the same effect on the coverage as a whole, without exception, failure of the ITSX produced the most dramatic results. A satellite's RTC value is most effected by ITSX failure. In each test case, the satellites with failed ITSX were ranked last with respect to CCC, regardless of their responsivity value. These satellites were always chosen as spares in the initial solution. For the real data, there were six satellites with failed ITSX components. Three unique solutions yielded similar coverage results. In each of these three cases, all of the spares were satellites with failed ITSX components. These results could be used to reduce the size of future problems. Eliminating satellite's with failed ITSX components from basis contention would reduce the size of the problem considerably. This, however, is not an option when the number of satellites possessing failed ITSX exceeds the number of spares.

Contrary to this argument, the solution at iteration 7 (Test Case 2) yielded a coverage nearly equaling the initial solution (iteration 1). Most notable about this result was that of the four spares, only one had a failed ITSX. This supports the assertion that CCC is not a perfect indicator of satellite value and the importance of satellite interaction as an area for future research.

V. Conclusions and Recommendations

Overview

The heuristic defined, evaluated, and exercised in this research provides AFTAC with a well-defined methodology for determining which 24 satellites should be monitored for NDS. The heuristic demonstrated a strong performance for a wide range of theoretical inputs. Using state-of-health inputs from the current constellation, the heuristic generated a solution yielding greater coverage than satellites currently being monitored.

Conclusions

The coverage contribution coefficient (CCC) was established and defined as a readily quantifiable indicator of satellite value. The CCC was a better predictor of overall satellite value than single dimensional criteria such as optical sensor sensitivity, real-time communications, or the penalty function. Optimizing the knapsack function based on CCC yielded the highest coverage value in all three test cases and for the real data. The use of test cases benchmarked the heuristics performance with varied failure inputs. The results proved that the heuristic was robust enough to handle these scenarios.

Though the iterative portion of the heuristic did not lead to any increase in coverage from the current solution, it should not be discarded. None of the test cases lead to an initial solution in which one of the planes was left without any satellites (the initial solution never left any one orbital plane with less than 3 satellites). In such a case, the initial solution would not likely yield the best coverage. Coverage would be expected to increase when satellites were placed in the void plane during subsequent iterations.

Though the coverage contribution coefficient proved to be a reliable proxy for satellite value, the task of thoroughly quantifying satellite interaction remained daunting. In several instances solutions with lesser total CCC value produced greater coverage than solutions with higher aggregate CCC, because satellite value was not fully accounted for by CCC. This proved that interaction among satellites was important and was not adequately represented in CCC.

The effects from communications component failures were consisted with the scaled values from the penalty function. ITSX failure clearly had the greatest effects. Satellites with failed ITSX components were consistently designated as spares in the solutions with the greatest coverage. When the number of satellites with ITSX failures exceeds the number of spares, multiple solutions yielding similar coverage are likely. Multiple "good" solutions provides AFTAC more insight than attempting to isolate a single best solution. The best solution might not always be feasible, and it is important to provide good alternatives. Re-run the calculations no more than quarterly unless there is a component failure. Responsivity degradation might alter the answer slightly.

Recommendations

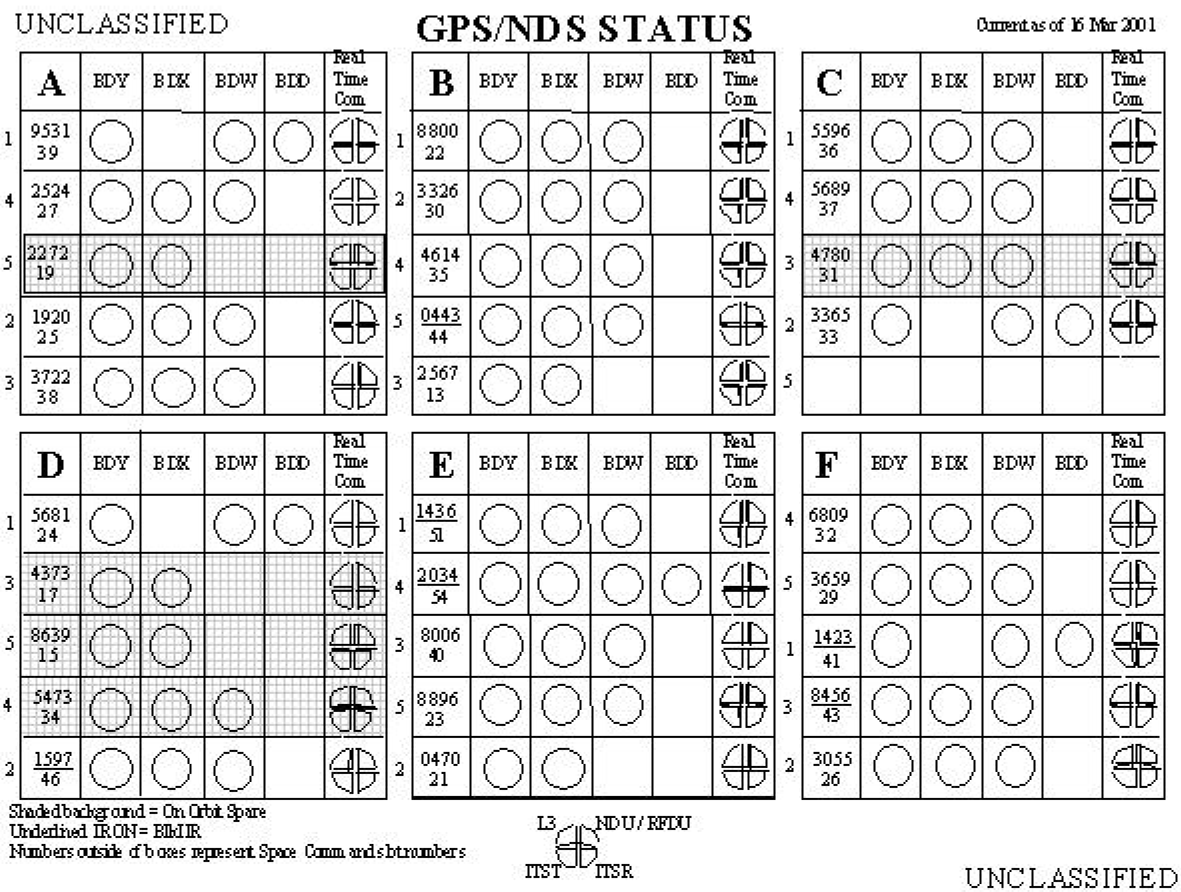
The solution presented in this research is only valid as long as the constellations state of health remains the same. Changes to the constellation including the addition of new satellites or component failures on an existing satellite require the heuristic to be performed to determine if a basis change needs to be made.

In this research, STK was used to compute RTC for the satellites in each case. The heuristic depends on the computation of real-time connectivity for each of the satellites. Computing this parameter is relatively simple and could easily be generated within the

confines of the GPS/MS platform. This addition to GPSM/S would provide the best means to continually apply the heuristic technique.

This research was constrained by the availability of GPSM/S. The heuristic presented was constructed based on the knowledge that access to the software was limited. A much more complete analysis with regards to the role of satellite interaction would be possible with a more complex heuristic such as Tabu Search or a Genetic Algorithm. Both these techniques would require the researcher to spend a significant amount of time with GPSM/S to accommodate a large number of test runs.

Appendix A. GPS NDS Status



Appendix B. Heuristic Results

Test Case 1:

Table 10. Heuristic Progression (Test Case 1)

Iteration	9531-A1	1920-A2	3722-A3	2524-A4	2272-A5	8800-B1	3326-B2	2567-B3	4614-B4	443-B5	5596-C1	3365-C2	4780-C3	5689-C4	5681-D1	1597-D2	5473-D4	8639-D5	1436-E1	470-E2	8006-E3	2034-E4	8896-E5	1423-F1	3055-F2	8456-F3	6809-F4	3659-F5
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	0	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
3	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
4	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
5	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
6	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
7	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0

Table 11. CCC Ranks (Test Case 1)

	8006-E3	1423-F1	1436-E1	1597-D2	8456-F3	443-B5	2034-E4	5473-D4	3055-F2	2524-A4	2567-B3	470-E2	3722-A3	3326-B2	5689-C4	8800-B1	9531-A1	8639-D5	2272-A5	3365-C2	3659-F5	5681-D1	8896-E5	6809-F4	5596-C1	4614-B4	1920-A2	4780-C3
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

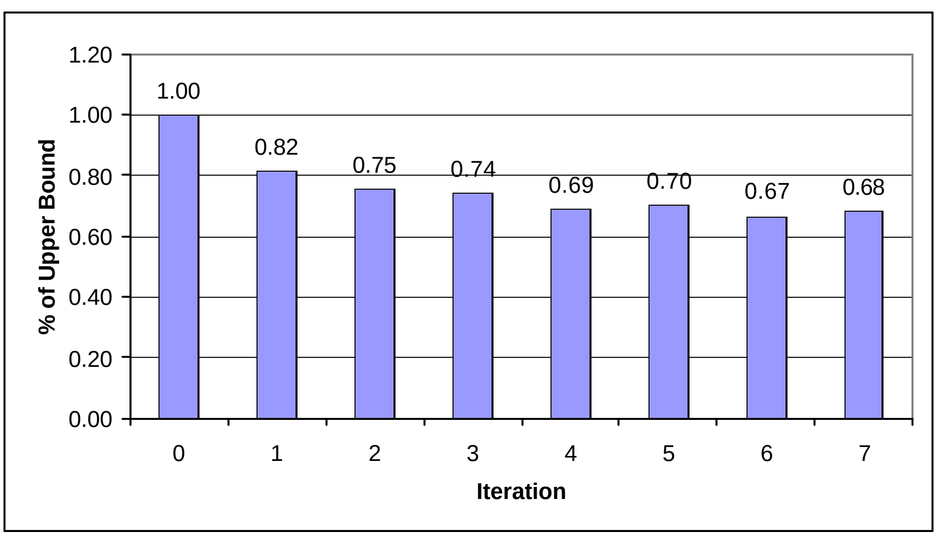


Figure 16. Heuristic Results (Test Case 1)

Test Case 2:

Table 12. Heuristic Progression (Test Case 2)

Iteration	9531-A1	1920-A2	3722-A3	2524-A4	2272-A5	8800-B1	3326-B2	2567-B3	4614-B4	443-B5	5596-C1	3365-C2	4780-C3	5689-C4	5681-D1	1597-D2	5473-D4	8639-D5	1436-E1	470-E2	8006-E3	2034-E4	8896-E5	1423-F1	3055-F2	8456-F3	6809-F4	3659-F5
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1
2	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
3	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
4	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
5	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
6	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
7	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0

Table 13. CCC Ranks (Test Case 2)

	1423-F1	1597-D2	1436-E1	8456-F3	3055-F2	5473-D4	5689-C4	2034-E4	443-B5	1920-A2	4614-B4	2524-A4	5681-D1	3326-B2	2272-A5	8896-E5	8006-E3	2567-B3	3659-F5	3722-A3	3365-C2	8800-B1	5596-C1	6809-F4	4780-C3	9531-A1	8639-D5	470-E2
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

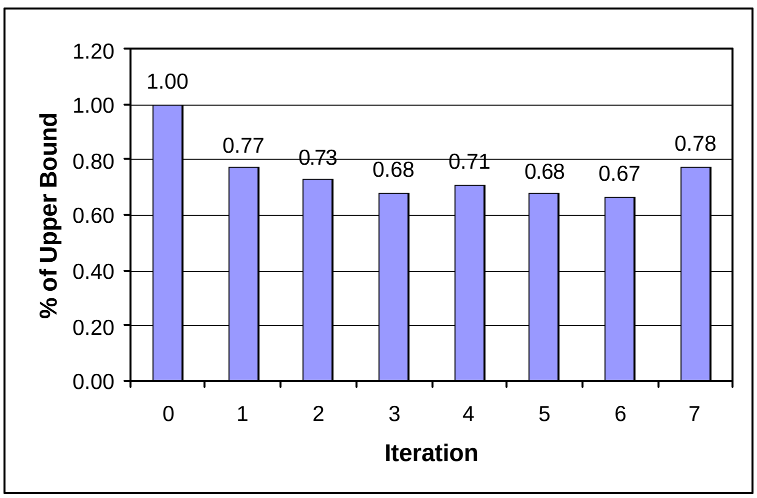


Figure 17. Heuristic Results (Test Case 2)

Test Case 3:

Table 14. Heuristic Progression (Test Case 3)

Iteration	9531-A1	1920-A2	3722-A3	2524-A4	2272-A5	8800-B1	3326-B2	2567-B3	4614-B4	443-B5	5596-C1	3365-C2	4780-C3	5689-C4	5681-D1	1597-D2	5473-D4	8639-D5	1436-E1	470-E2	8006-E3	2034-E4	8896-E5	1423-F1	3055-F2	8456-F3	6809-F4	3659-F5
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1
2	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
3	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
4	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
5	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
6	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1
7	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0

Table 15. CCC Ranks (Test Case 3)

	1423-F1	1597-D2	443-B5	8456-F3	1436-E1	5473-D4	2034-E4	8800-B1	2567-B3	8896-E5	3722-A3	5681-D1	1920-A2	9531-A1	3055-F2	470-E2	3365-C2	2272-A5	4780-C3	3659-F5	6809-F4	2524-A4	8639-D5	3326-B2	4614-B4	5596-C1	5689-C4	8006-E3
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

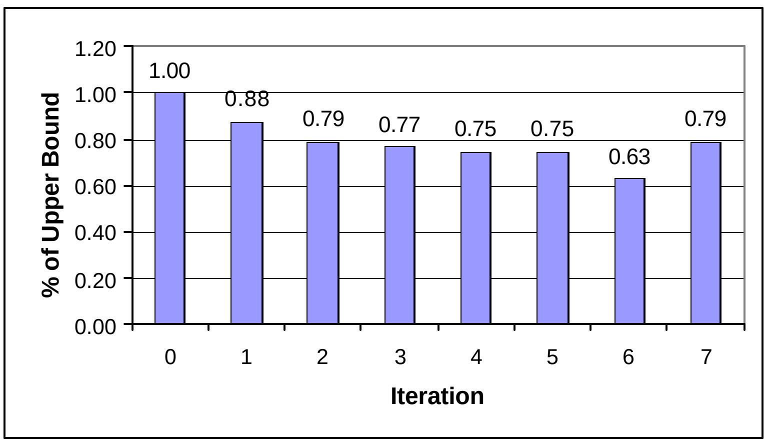


Figure 18. Heuristic Results (Test Case 3)

Real Data:

Table 16. Heuristic Progression (Real Data)

Iteration	9531-A1	1920-A2	3722-A3	2524-A4	8800-B1	3326-B2	2567-B3	4614-B4	443-B5	5596-C1	3365-C2	4780-C3	5689-C4	5681-D1	1597-D2	5473-D4	8639-D5	1436-E1	470-E2	8006-E3	2034-E4	8896-E5	1423-F1	3055-F2	8456-F3	6809-F4	3659-F5
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
4	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1
5	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1
6	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0
7	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1

Table 17. CCC Ranks (Real Data)

	1597-D2	8456-F3	1423-F1	443-B5	1436-E1	2567-B3	2034-E4	3055-F2	5689-C4	3659-F5	5596-C1	470-E2	3722-A3	3326-B2	8639-D5	5681-D1	4614-B4	1920-A2	9531-A1	6809-F4	8006-E3	3365-C2	8896-E5	2524-A4	4780-C3	8800-B1	5473-D4
Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

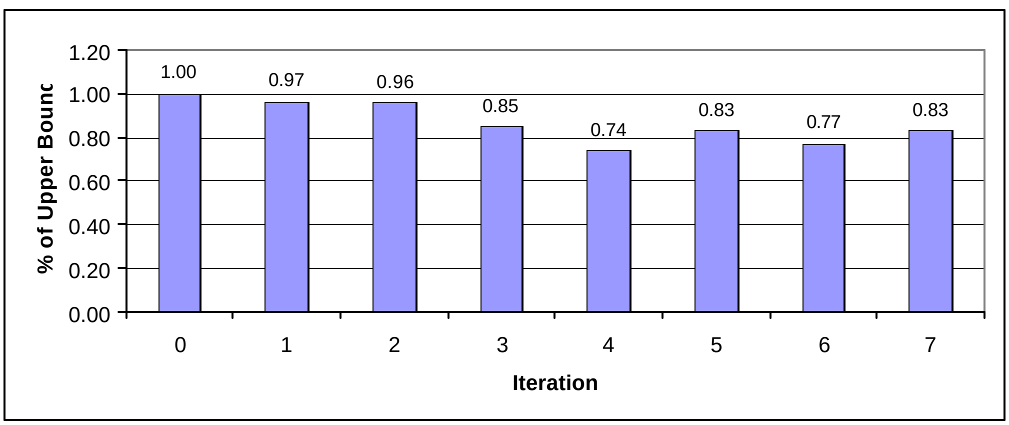


Figure 19. Heuristic Results (Real Data)

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14. ABSTRACT The United States Nuclear Detonation Detection System (USNDS) relies, in part, on space based sensors onboard NAVSTAR Global Positioning System (GPS) satellites to detect endo- and exo-atmospheric nuclear blasts. Though there are currently over 24 operational GPS satellites, ground based antennas are only capable of actively monitoring 24 satellites at a time. Personnel at the Air Force Technical Applications Center (AFTAC) are primarily responsible for determining which 24 satellites should be monitored. The current state-of-health of each satellite varies widely and thus complicated the decision making process. AFTAC desires a well-defined methodology for selecting 24 satellites to maximize global coverage. This research introduced a means to numerically quantify each satellites individual contribution to the coverage provided by the constellation as a whole. A heuristic search heuristic was constructed to generate a set of possible combinations of satellites yielding high global coverage.

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